US007183995B2

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Pleva et al.

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(45) **Date of Patent: Feb. 27, 2007**

(54) **ANTENNA CONFIGURATIONS FOR REDUCED RADAR COMPLEXITY**

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(73) Assignee: **Raytheon Company**, Waltham, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 119 days.

(21) Appl. No.: **10/619,020**

(22) Filed: **Jul. 14, 2003**

(65) **Prior Publication Data**

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Related U.S. Application Data

(63) Continuation-in-part of application No. 10/376,179, filed on Feb. 27, 2003, now Pat. No. 6,970,142, which is a continuation-in-part of application No. 10/293,880, filed on Nov. 13, 2002, now Pat. No. 6,995,730, which is a continuation-in-part of application No. 09/932,574, filed on Aug. 16, 2001, now Pat. No. 6,642,908.

(51) **Int. Cl.**
H01Q 3/24 (2006.01)

(52) **U.S. Cl.** **343/853**; 343/876; 342/374

(58) **Field of Classification Search** 343/853, 343/876; 342/371–375, 368
See application file for complete search history.

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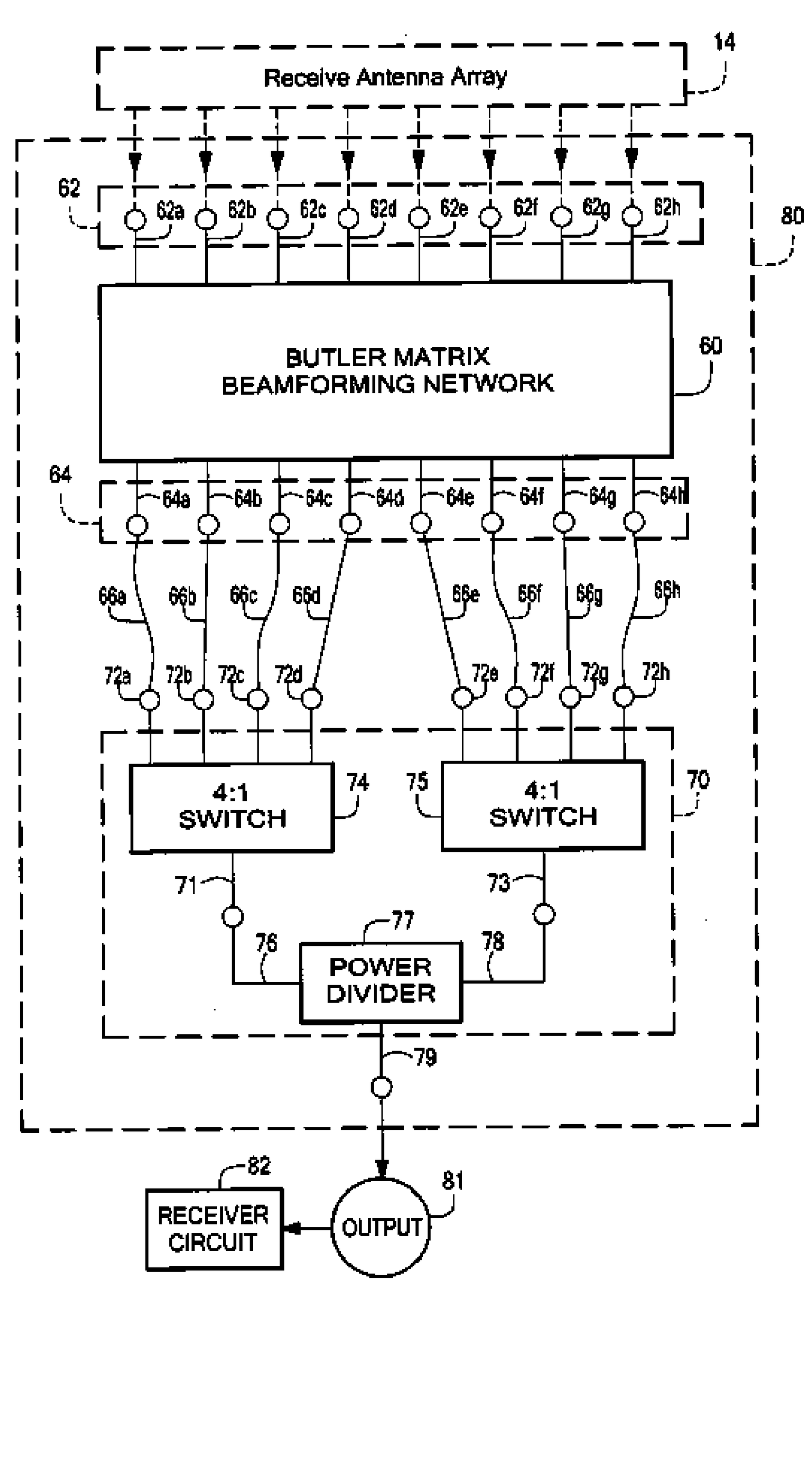
Primary Examiner—Michael C. Wimer
(74) *Attorney, Agent, or Firm*—Daly, Crowley, Mofford & Durkee, LLP

(57) **ABSTRACT**

A transmit and receiving system including a first array including at least one antenna element disposed to provide a transmit antenna. The system further includes a second array having a second different plurality of antenna elements disposed to provide a receive antenna. The first array is coupled to a switching system, which is operative to selectively form at least one transmit beam. The second array is coupled to a beam combining system, which is operative to selectively form a plurality of receive beams.

19 Claims, 14 Drawing Sheets



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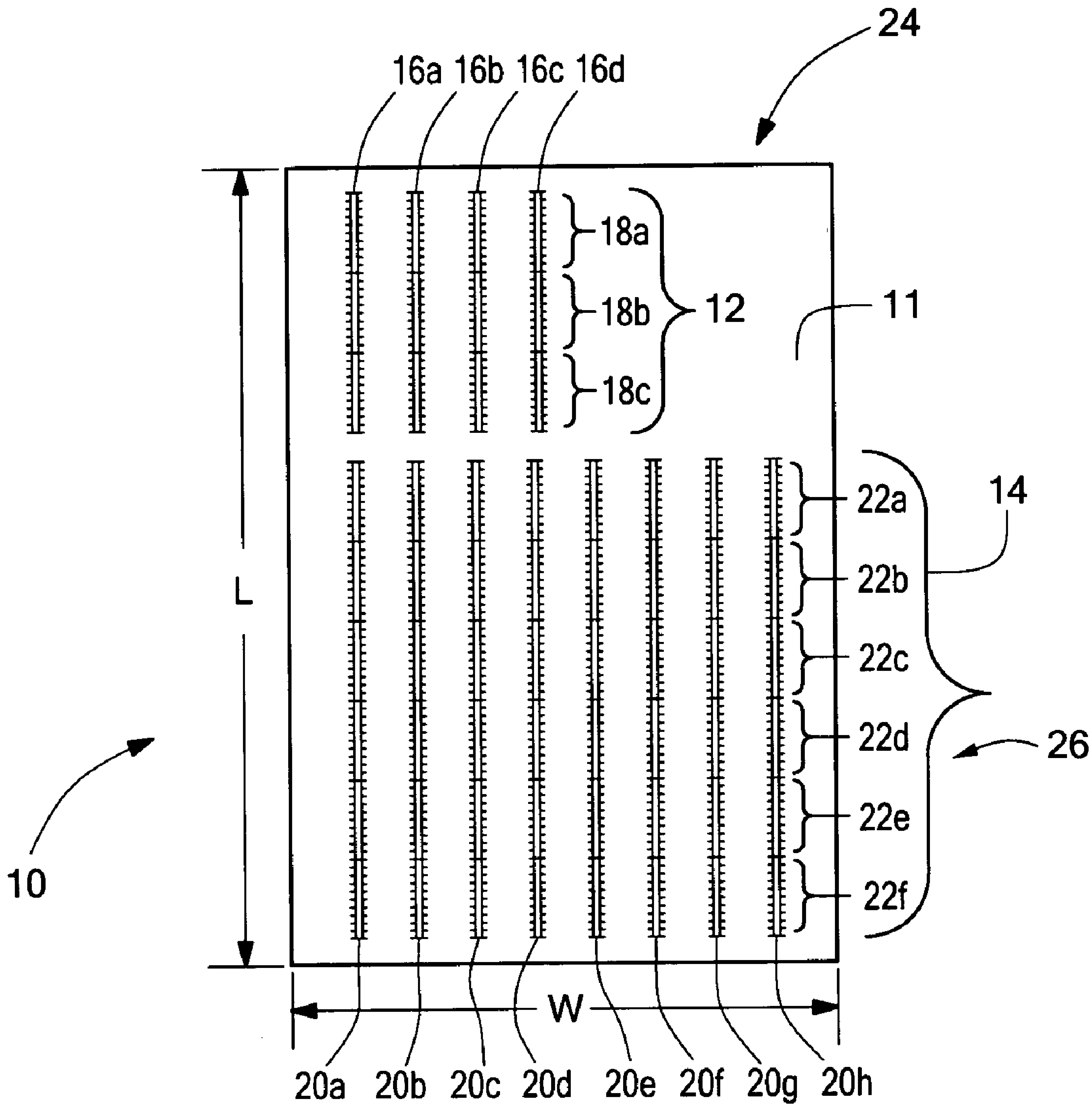

24
16a 16b 16c 16d
18a
18b
18c
12
11
14
22a
22b
22c
22d
22e
22f
26
L
10
W
20a 20b 20c 20d 20e 20f 20g 20h

FIG. 1

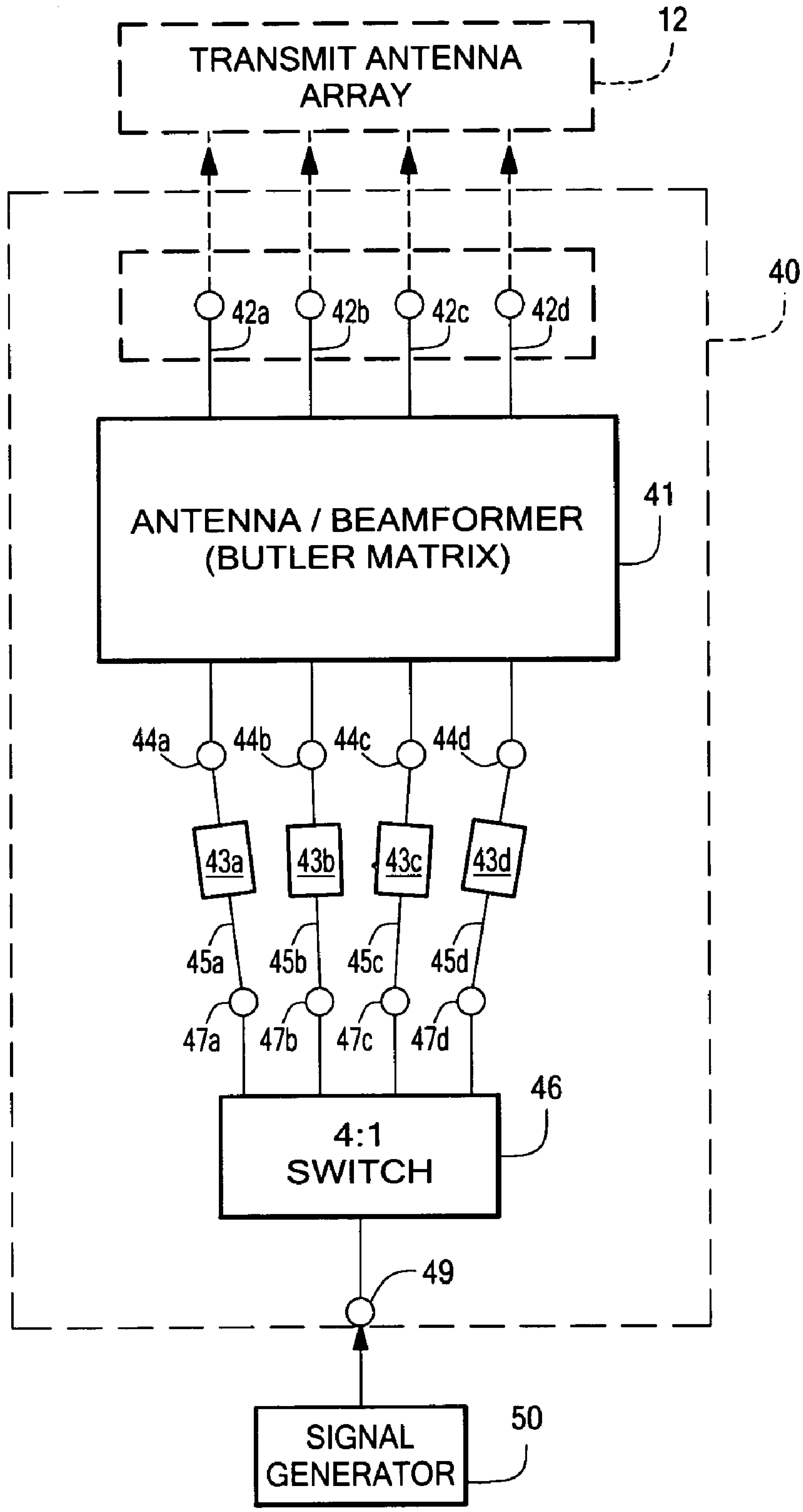

TRANSMIT ANTENNA ARRAY
12
40
42a
42b
42c
42d
ANTENNA / BEAMFORMER (BUTLER MATRIX)
41
44a
44b
44c
44d
43a
43b
43c
43d
45a
45b
45c
45d
47a
47b
47c
47d
4:1 SWITCH
46
49
SIGNAL GENERATOR
50

FIG. 2

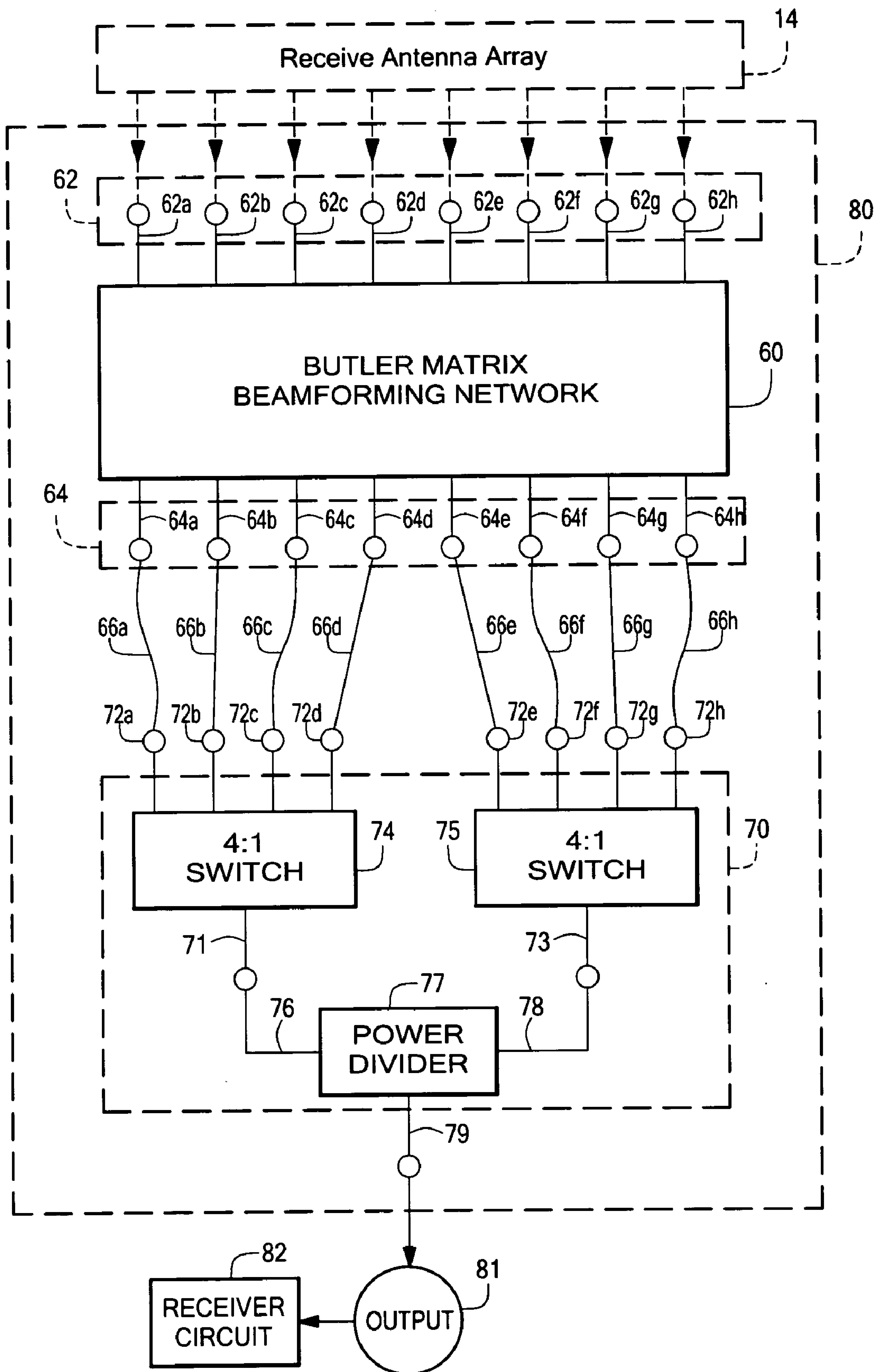

14
Receive Antenna Array
80
62
62a
62b
62c
62d
62e
62f
62g
62h
BUTLER MATRIX
BEAMFORMING NETWORK
60
64
64a
64b
64c
64d
64e
64f
64g
64h
66a
66b
66c
66d
66e
66f
66g
66h
72a
72b
72c
72d
72e
72f
72g
72h
4:1
SWITCH
74
75
4:1
SWITCH
70
71
73
77
76
78
POWER
DIVIDER
79
82
RECEIVER
CIRCUIT
81
OUTPUT

FIG. 3

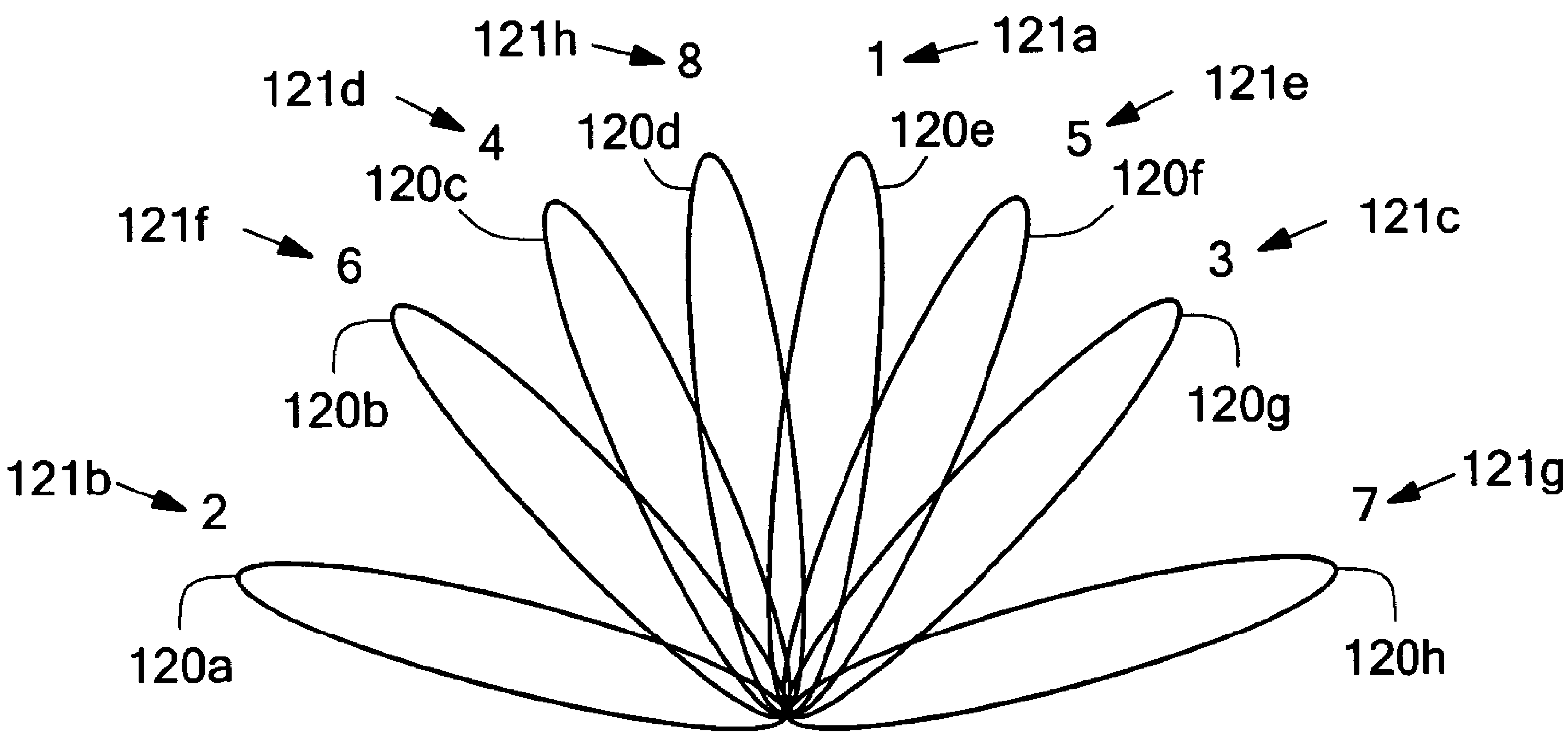

121h
8
1
121a
121d
4
120d
120e
5
121e
120c
120f
121f
6
3
121c
120b
120g
121b
2
7
121g
120a
120h

FIG. 4

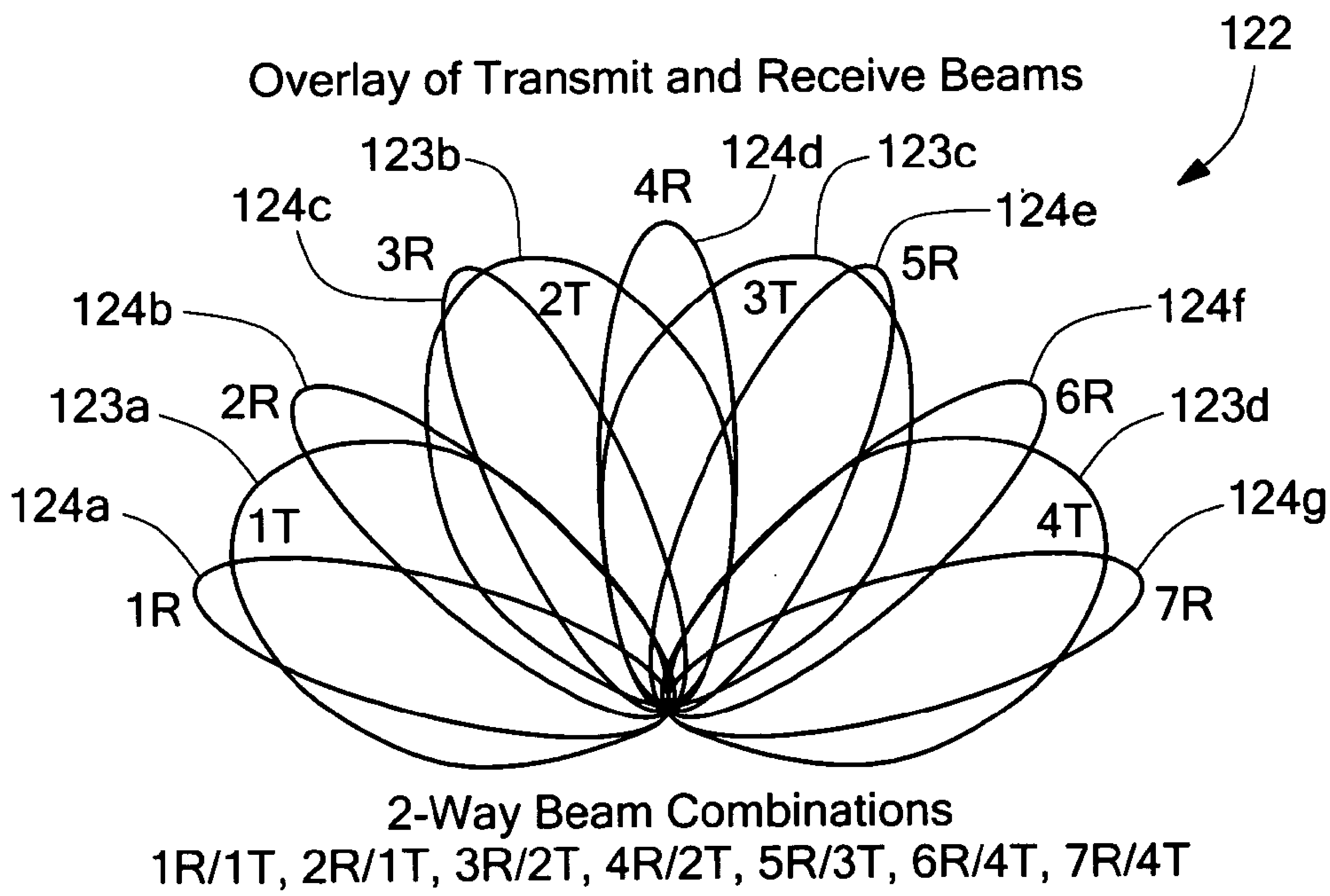

122
Overlay of Transmit and Receive Beams
123b
124d
123c
4R
124c
124e
3R
5R
2T
3T
124b
124f
123a
2R
6R
123d
124a
1T
4T
124g
1R
7R
2-Way Beam Combinations
1R/1T, 2R/1T, 3R/2T, 4R/2T, 5R/3T, 6R/4T, 7R/4T

FIG. 4A

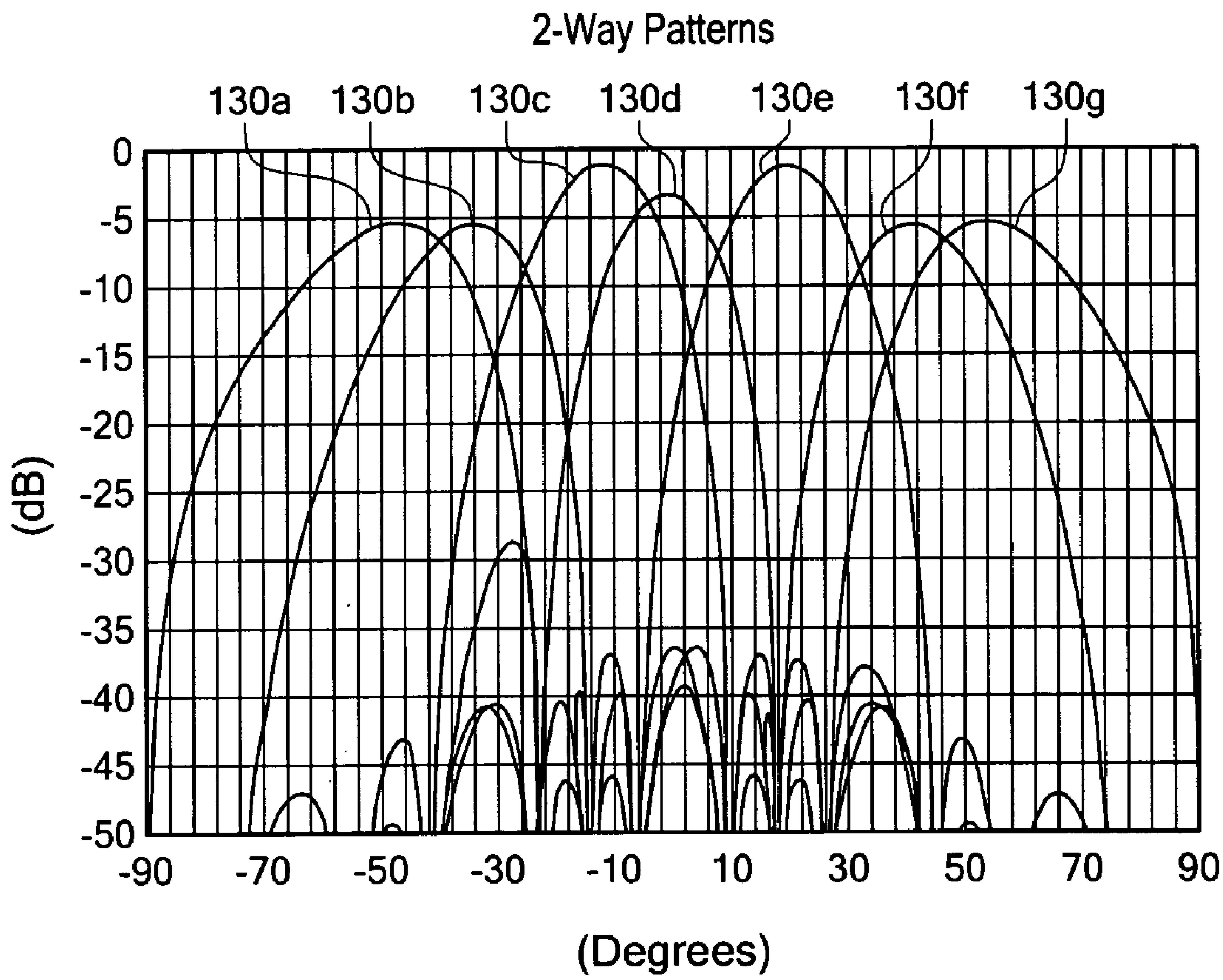

2-Way Patterns
130a
130b
130c
130d
130e
130f
130g
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
(dB)
-90
-70
-50
-30
-10
10
30
50
70
90
(Degrees)

FIG. 5

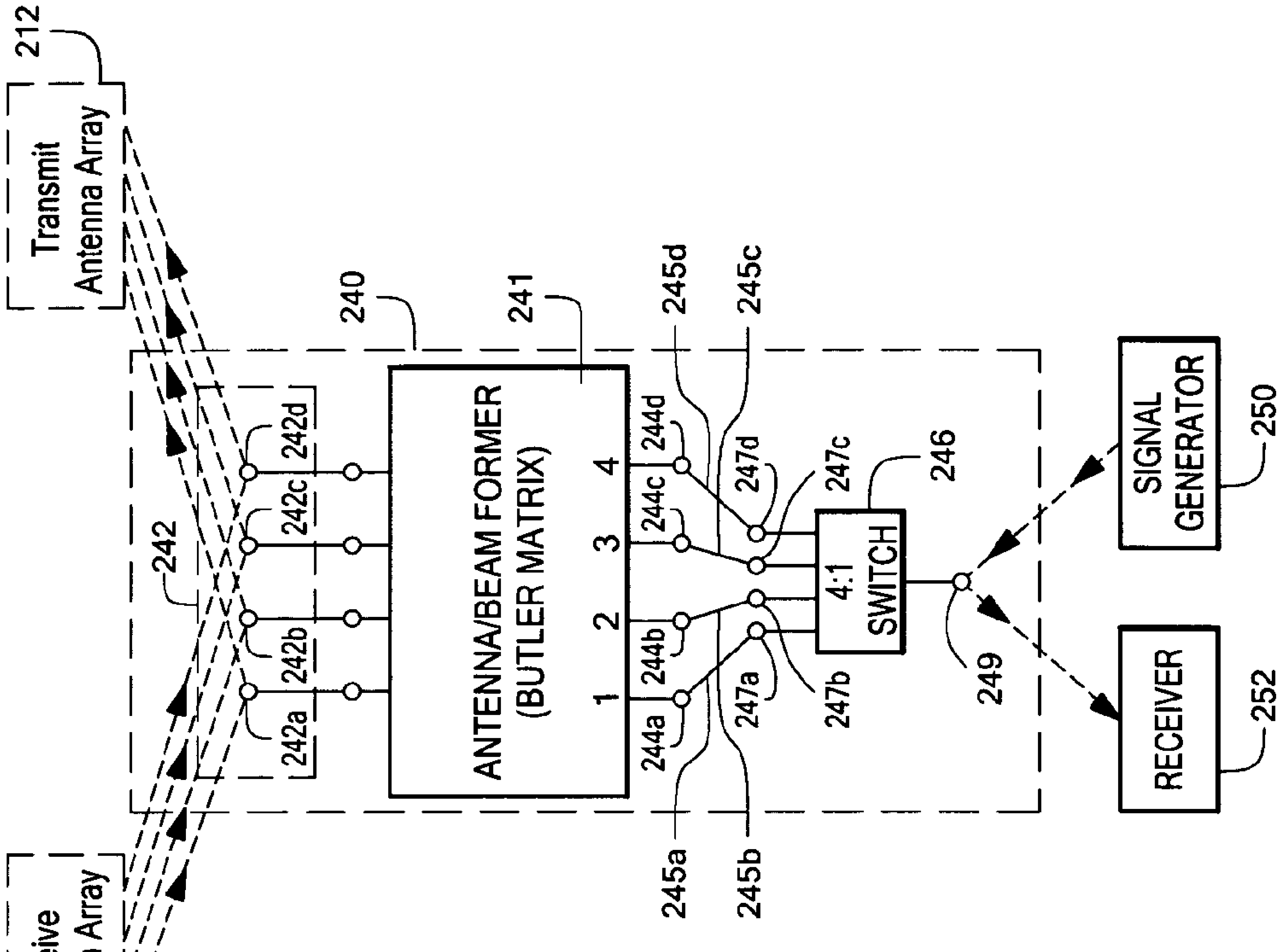

212
Transmit Antenna Array
214
Receive Antenna Array
240
241
ANTENNA/BEAM FORMER (BUTLER MATRIX)
242
242a
242b
242c
242d
1
2
3
4
244a
244b
244c
244d
245a
245b
245c
245d
247a
247b
247c
247d
246
4:1 SWITCH
249
SIGNAL GENERATOR
250
RECEIVER
252

FIG. 7

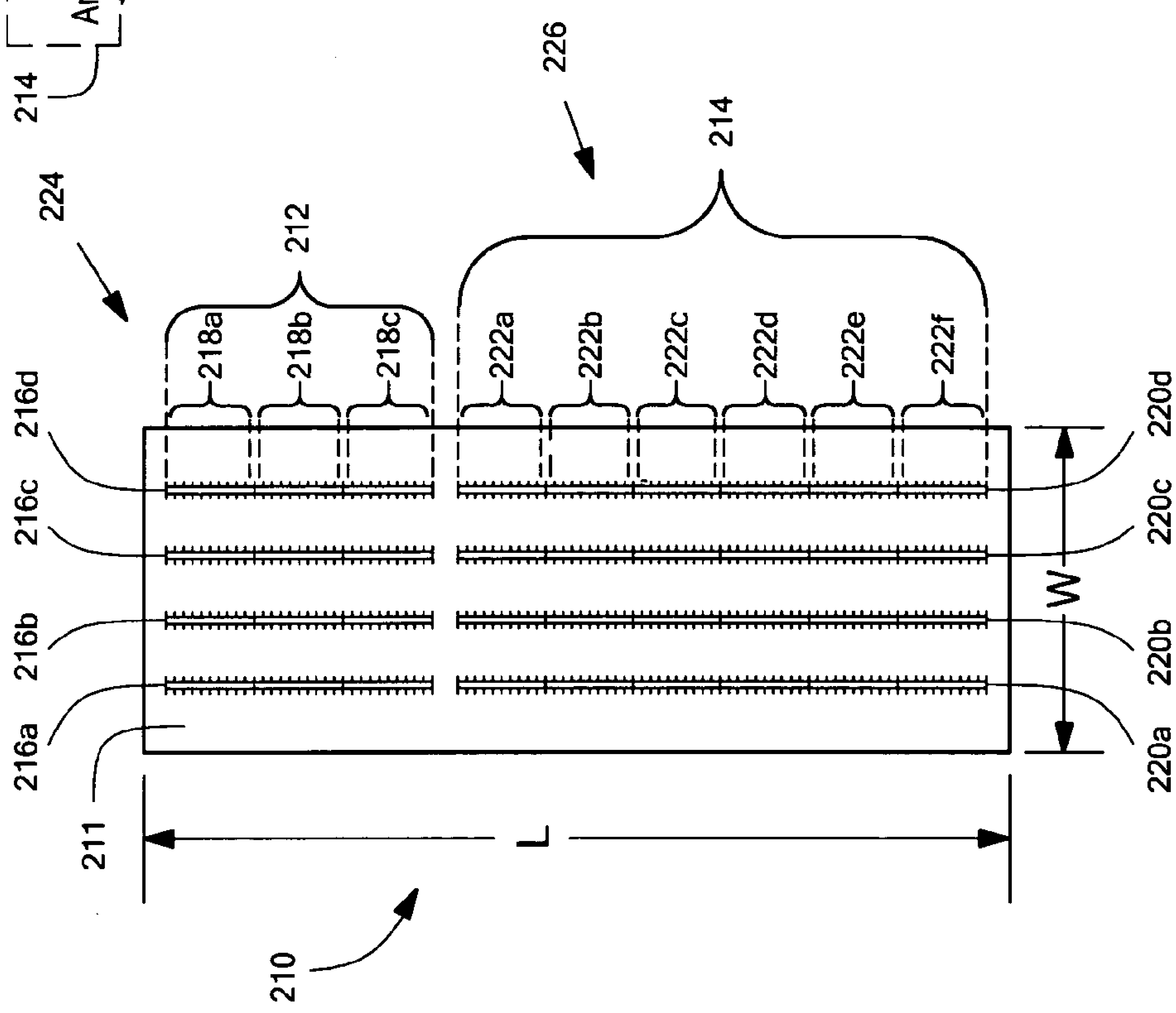

224
226
212
214
218a
218b
218c
222a
222b
222c
222d
222e
222f
216a
216b
216c
216d
220a
220b
220c
220d
211
W
L
210

FIG. 6

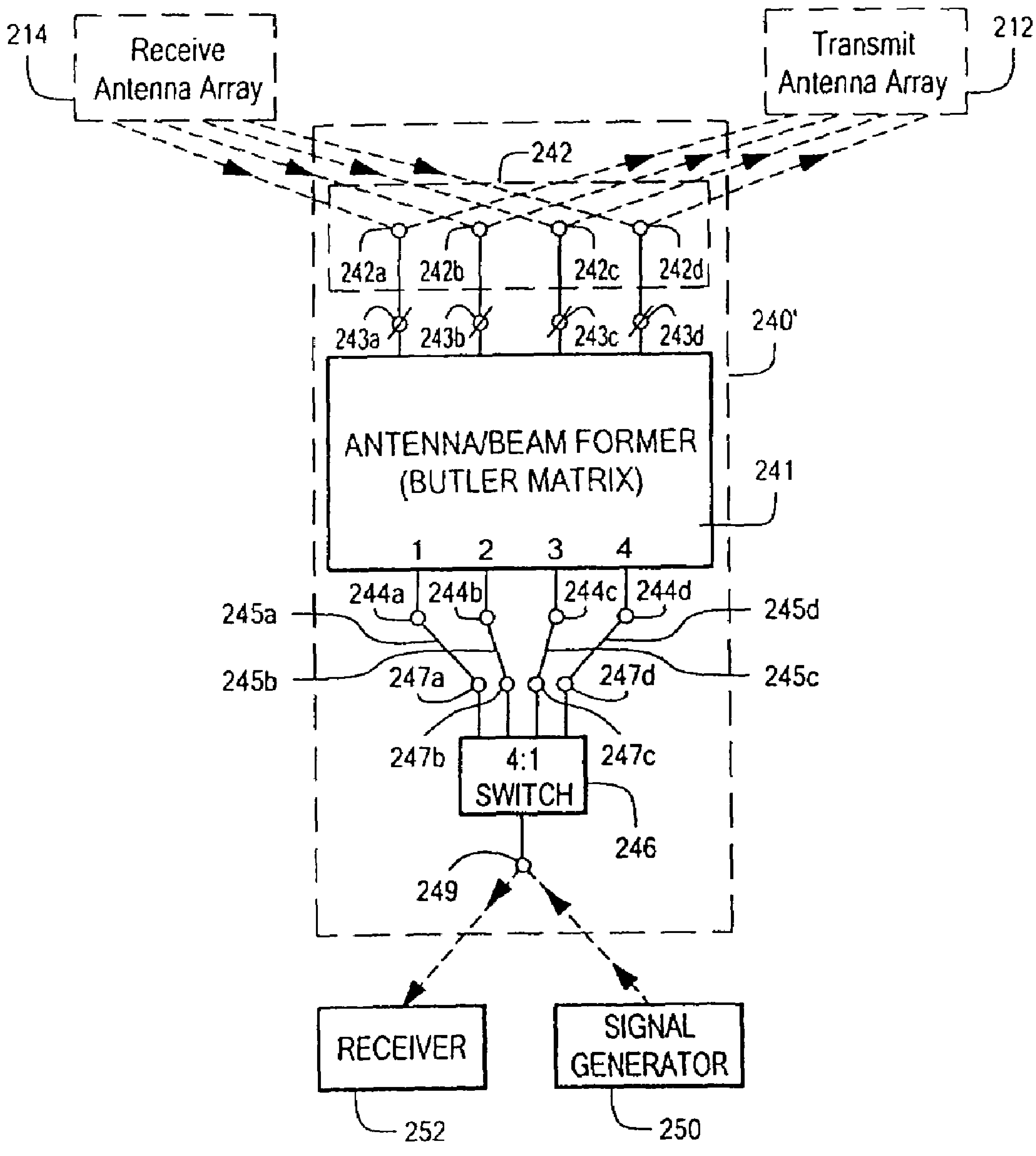
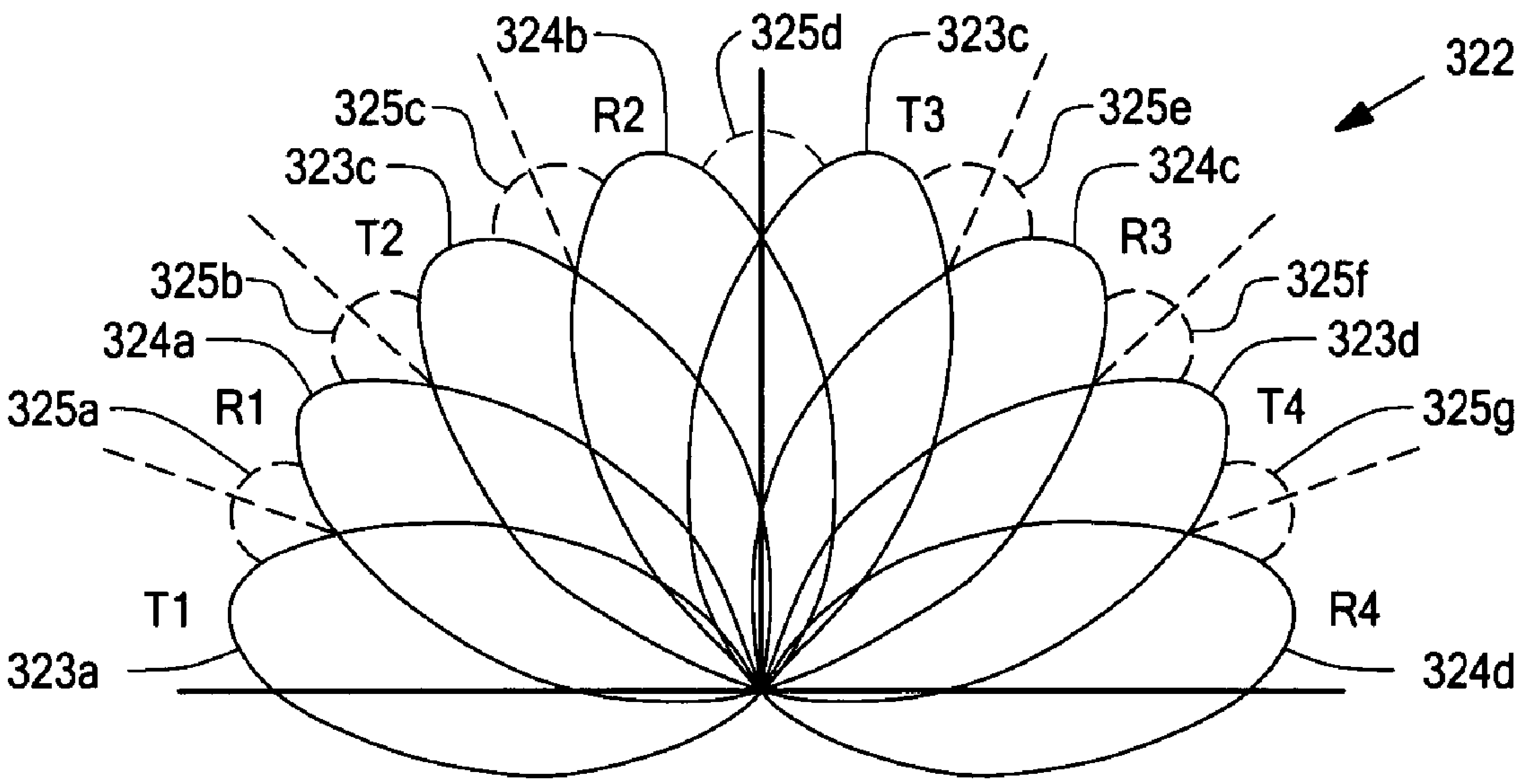

214
Receive Antenna Array
Transmit Antenna Array
212
242
242a
242b
242c
242d
243a
243b
243c
243d
240'
ANTENNA/BEAM FORMER (BUTLER MATRIX)
241
1
2
3
4
244a
244b
244c
244d
245a
245d
245b
245c
247a
247d
247b
247c
4:1 SWITCH
246
249
RECEIVER
SIGNAL GENERATOR
252
250

FIG. 7A

Overlay of Transmit and Receive Beams



Transmit and Receive Combinations
T1/R1, T2/R1, T2/R2, T3/R2, T3/R3, T4/R3, T4/R4

FIG. 8

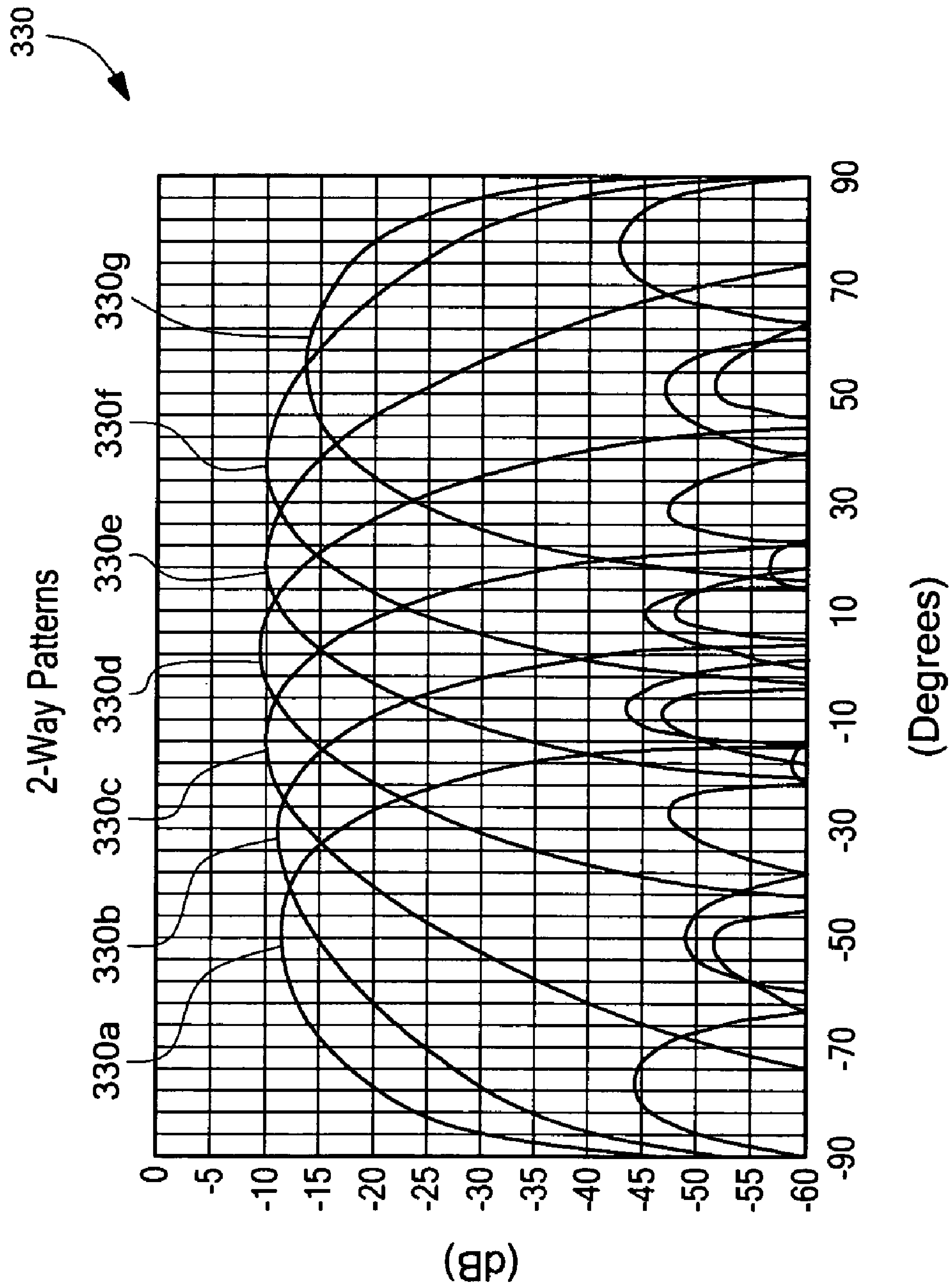

330
2-Way Patterns
330a
330b
330c
330d
330e
330f
330g
(dB)
(Degrees)

FIG. 9

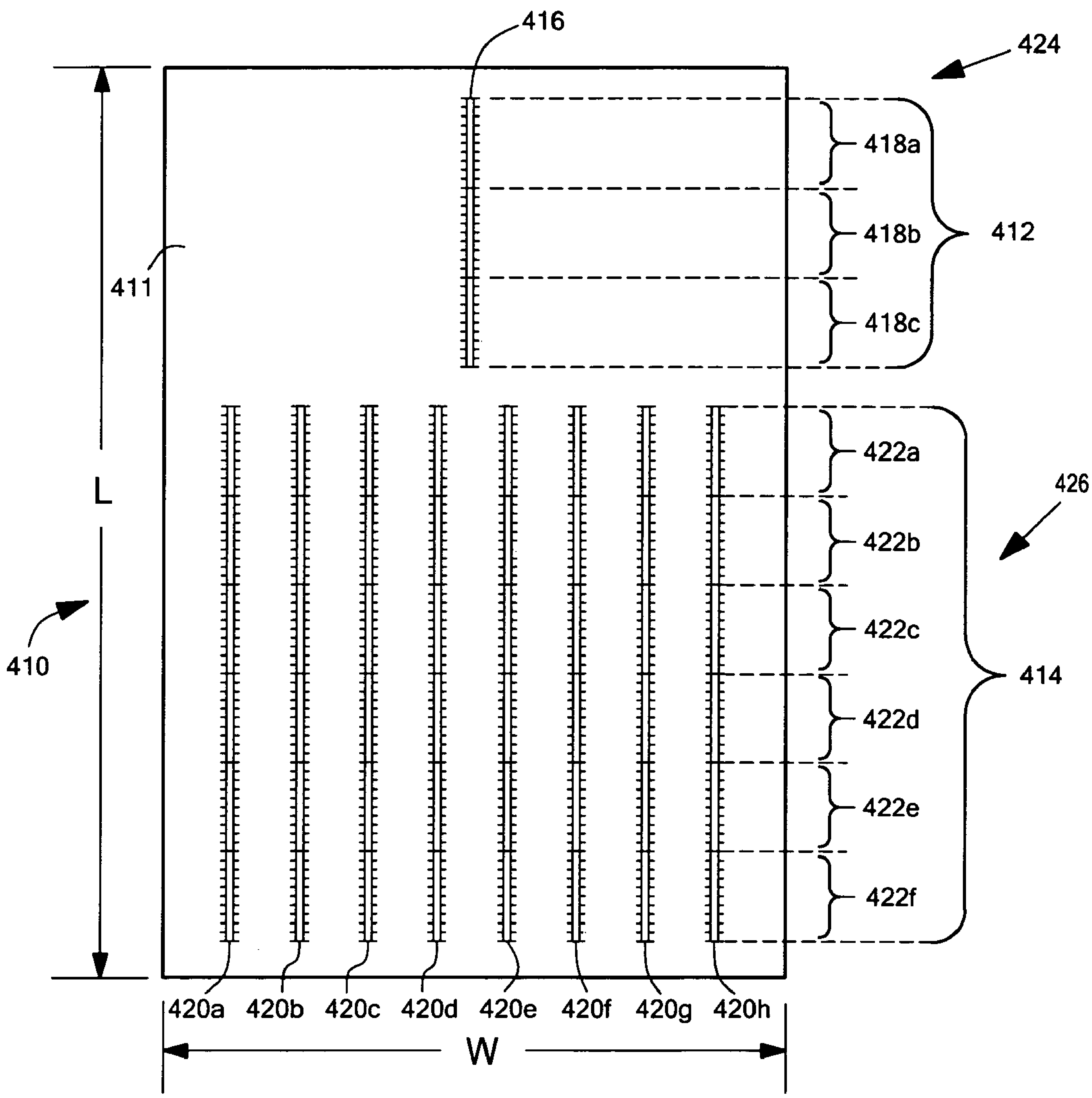

416
424
418a
418b
412
418c
411
L
422a
426
422b
422c
410
414
422d
422e
422f
420a
420b
420c
420d
420e
420f
420g
420h
W

FIG. 10

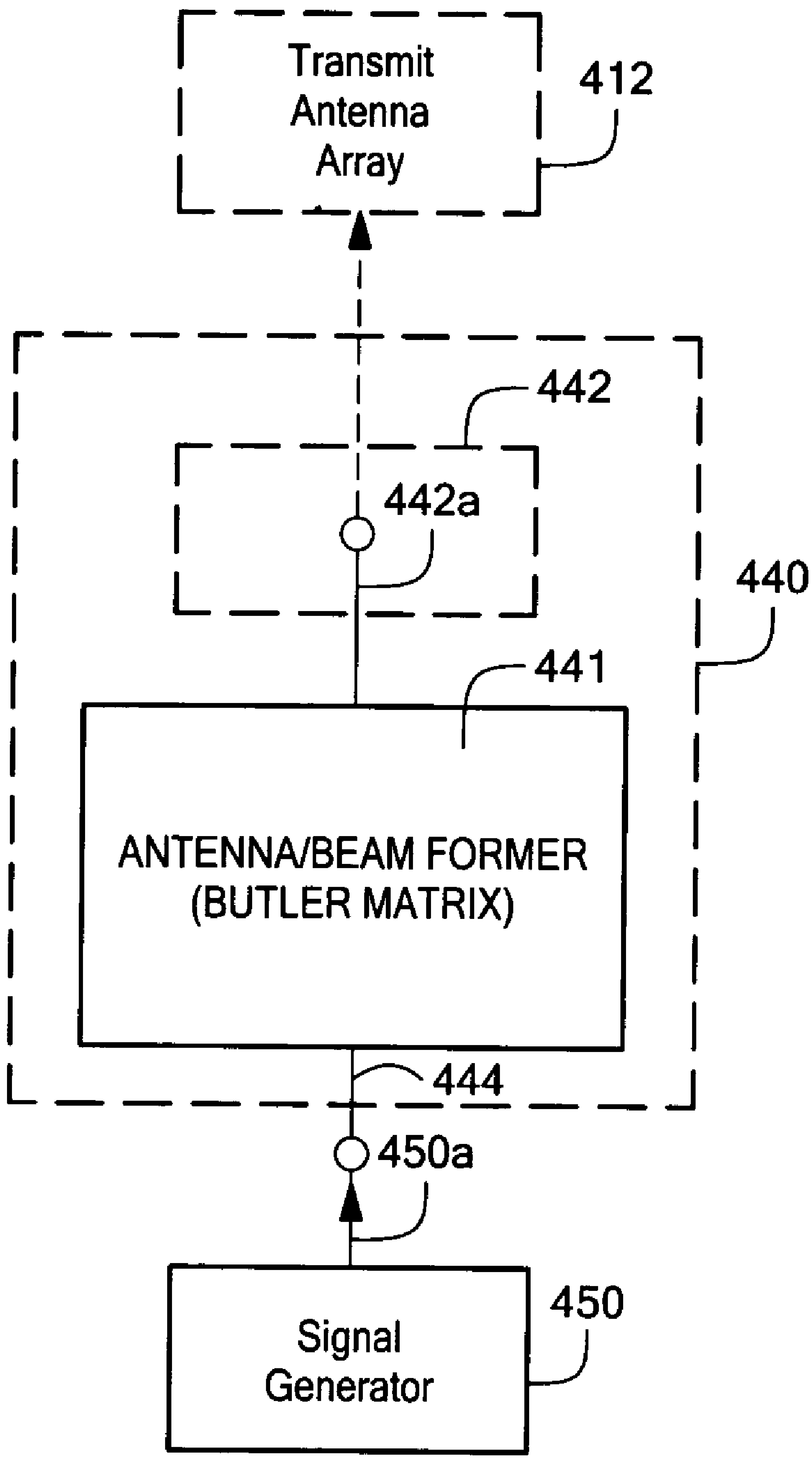

Transmit
Antenna
Array
412
442
442a
440
441
ANTENNA/BEAM FORMER
(BUTLER MATRIX)
444
450a
Signal
Generator
450

FIG. 11

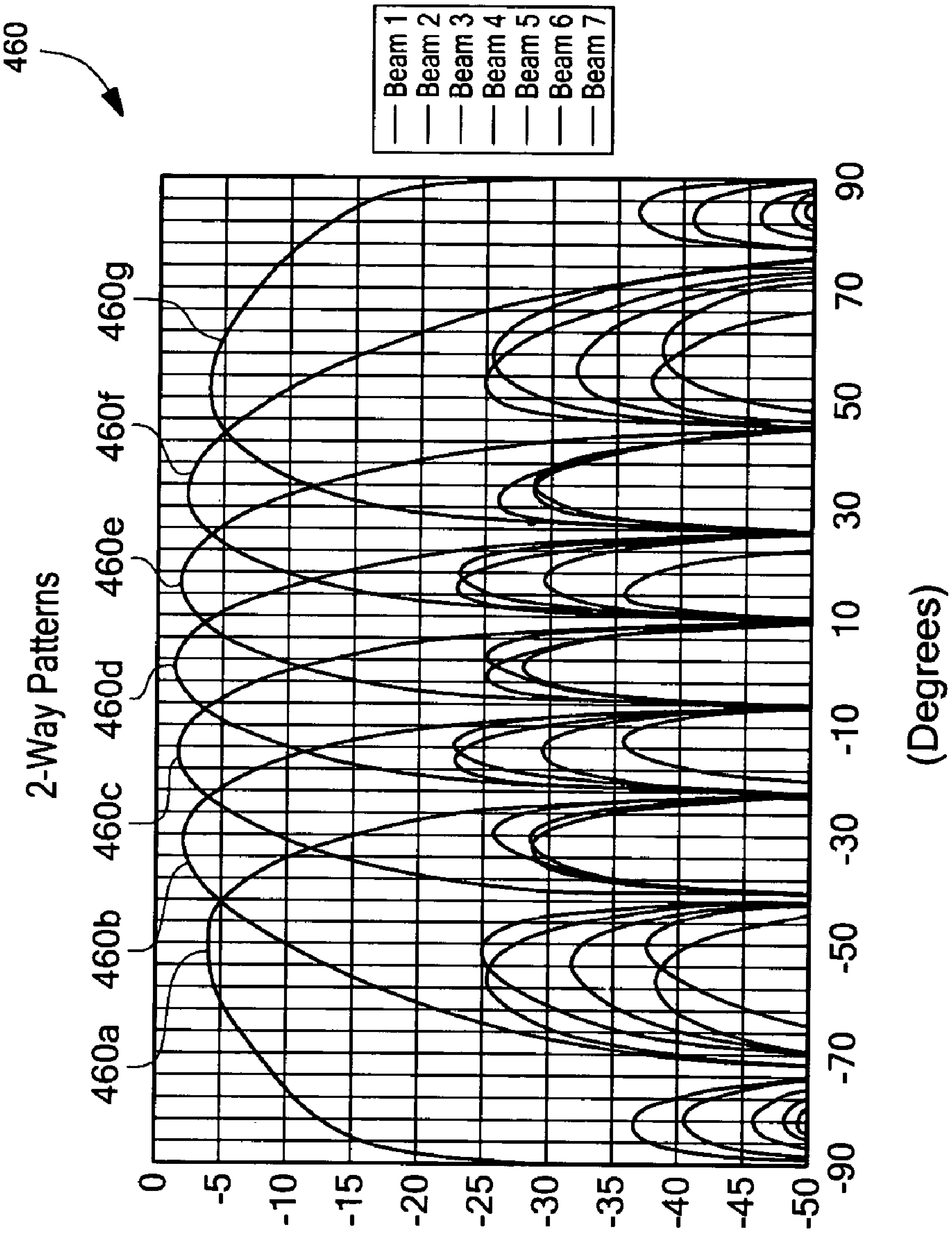
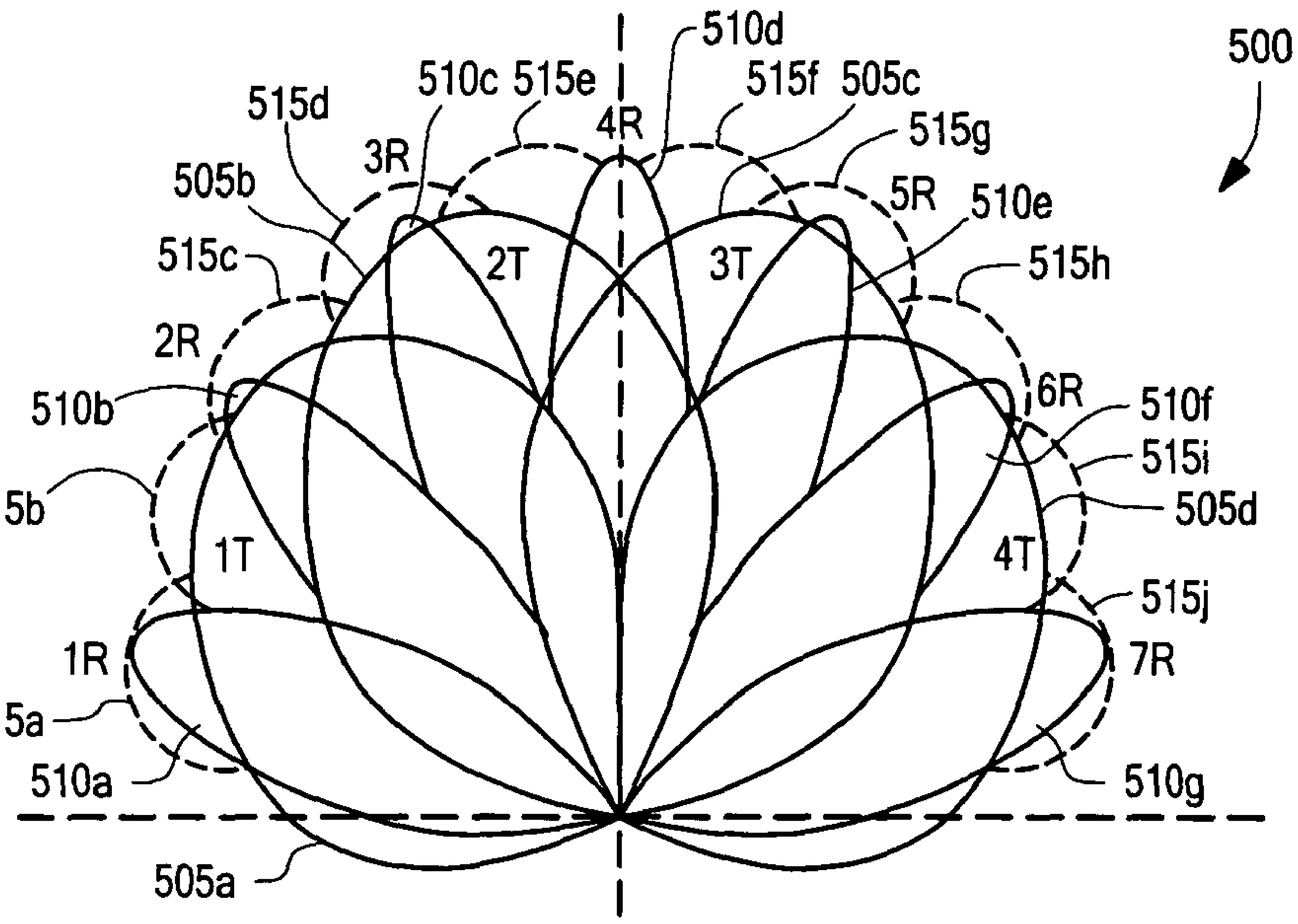

460
2-Way Patterns
460a
460b
460c
460d
460e
460f
460g
Beam 1
Beam 2
Beam 3
Beam 4
Beam 5
Beam 6
Beam 7
(dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-90
-70
-50
-30
-10
10
30
50
70
90
(Degrees)

FIG. 12

Overlay of Transmit and Receive Beams



2-Way Combinations

1R/1T, 2R/1T, 2R/2T, 3R/2T, 4R/2T, 4R/3T, 5R/3T, 6R/3T, 6R/4T, 7R/4T

510a 505a, 510b 505a, 510b 505b, 510c 505b, 510d 505b, 510d 505c, 510e 505c, 510f 505c, 510f 505d, 510g 505d

FIG. 13

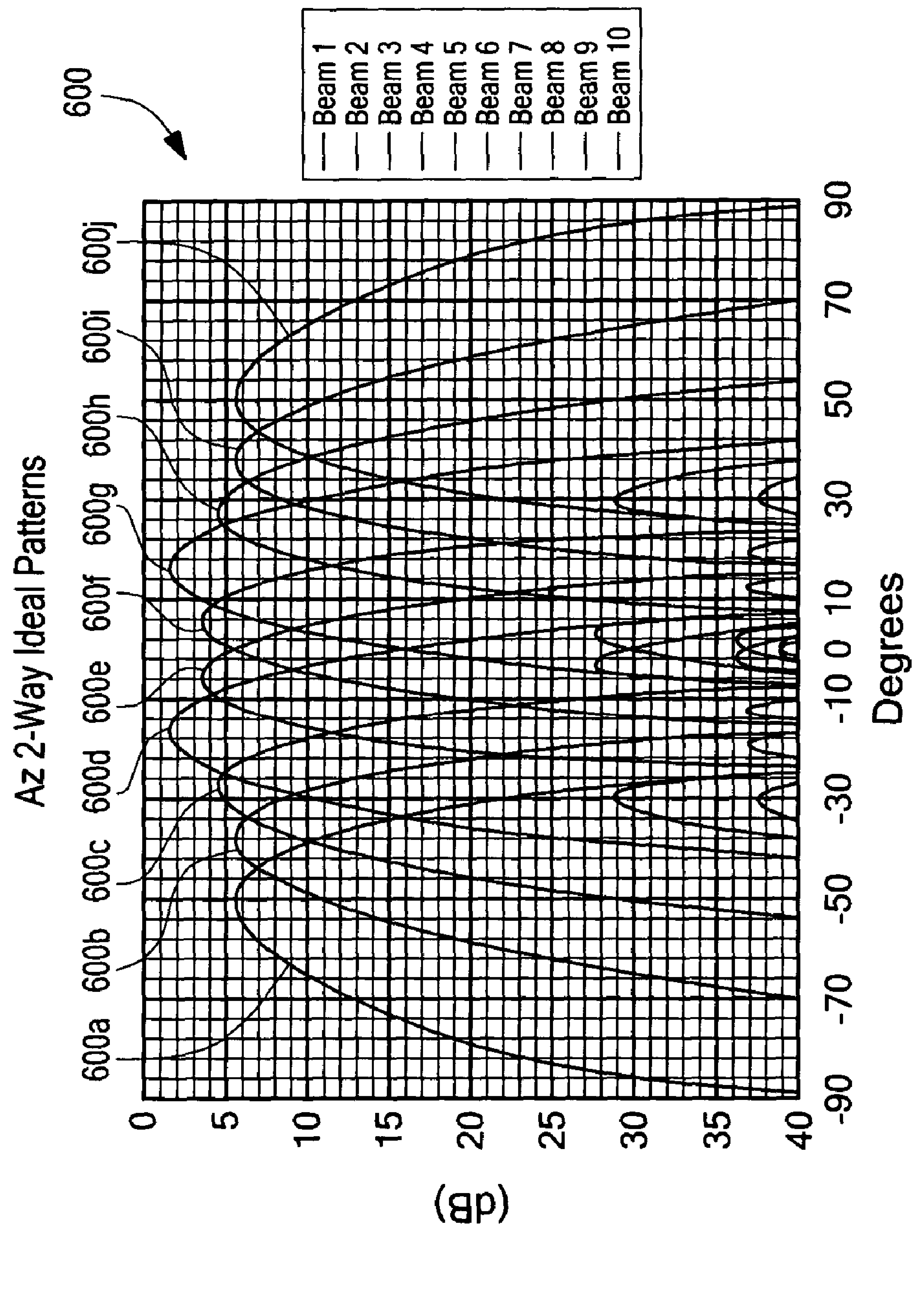

600
Az 2-Way Ideal Patterns
Beam 1
Beam 2
Beam 3
Beam 4
Beam 5
Beam 6
Beam 7
Beam 8
Beam 9
Beam 10
600a
600b
600c
600d
600e
600f
600g
600h
600i
600j
0 5 10 15 20 25 30 35 40
(dB)
-90 -70 -50 -30 -10 0 10 30 50 70 90
Degrees

FIG. 14

ANTENNA CONFIGURATIONS FOR REDUCED RADAR COMPLEXITY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a Continuation-in-Part of and claims the benefit of U.S. patent application Ser. No. 10/376,179 filed Feb. 27, 2003, now U.S. Pat. No. 6,970,142, which is a Continuation-in-Part of and claims the benefit of U.S. patent application Ser. No. 10/293,880, filed Nov. 13, 2002, now U.S. Pat. No. 6,995,730, which is a Continuation-in-Part of and claims the benefit of U.S. patent application Ser. No. 09/932,574, filed on Aug. 16, 2001, now U.S. Pat. No. 6,642,908, which are each hereby incorporated by reference.

STATEMENTS REGARDING FEDERALLY SPONSORED RESEARCH

Not applicable.

FIELD OF THE INVENTION

This invention relates to a transmit/receive system and more particularly to a transmit/receive system which utilizes an array antenna having asymmetric transmit and receive antennas.

BACKGROUND OF THE INVENTION

As is known in the art, there is an increasing trend to include radar systems in commercially available products. For example, it is desirable to include radar systems in automobiles, trucks boats, airplanes and other vehicle. Such radar systems must be compact and relatively low cost.

Furthermore, some applications have relatively difficult design parameters including restrictions on the physical size of the structure, as well as minimum operational performance requirements. Such competing design requirements make the design of such radar systems relatively challenging. Among the design challenges is the challenge to provide an antenna system which meets the design goals of being low cost, compact and have relatively high performance.

In automotive radar systems, for example, cost and size considerations are of considerable importance. Furthermore, in order to meet the performance requirements of automotive radar applications, (e.g. coverage area) an array antenna is required.

It would, therefore, be desirable to provide an antenna array that is compact which can operate in a high density circuit environment, and is relatively low cost to manufacture and yet provides an antenna array having relatively high performance characteristics.

SUMMARY OF THE INVENTION

In accordance with principles of the present invention, set forth is a transmit and receive system that is relatively compact and can operate in a high density circuit environment, and which is relatively low cost to manufacture and yet provides an antenna array having relatively high performance characteristics.

The transmit and receive system includes a first array including a first plurality of antenna element disposed to provide a transmit antenna. A beam switching system is coupled to the first array and is operative to form a plurality of transmit beams.

The transmit and receive system further includes a second array including a second plurality of antenna elements disposed to provide a receive antenna. A beam combining system is coupled to the second array and is operative to form a plurality of receive beams. In accordance with aspects of the present invention, predetermined ones of the plurality of transmit beams and predetermined ones of the plurality of receive beams are combined to form a plurality of two-way beams.

In another aspect of the present invention, a method of forming a plurality of two-way radiation beams using a transmit and receive system is set forth. The method includes controlling a transmit antenna array of the transmit and receive system to provide a plurality of transmit radiation beams. A receive antenna array of the transmit and receive system is also controlled to sense a plurality of receive radiation beams. Further, predetermined ones of the plurality of transmit beams and predetermined ones of the plurality of receive beams are combined to form the plurality of two-way radiation beams.

In an aspect, controlling the transmit antenna array includes controlling a beam switching system, which is coupled to the transmit antenna array, to provide the plurality of transmit radiation beams. In addition, controlling the receive antenna array includes controlling a beam combining system, which is coupled to the receive antenna array, to provide the plurality of receive radiation beams.

In accordance with one particular aspect of the present invention, predetermined ones of the plurality of transmit beams and predetermined ones of the plurality of receive beams are combined to form ten two-way radiation beams. More particularly, a first transmit radiation beam of the plurality of transmit radiation beams is combined with a first receive radiation beam of the plurality of receive radiation beams to provide a first two-way radiation beam. The first transmit radiation beam of the plurality of transmit radiation beams is combined with a second receive radiation beam of the plurality of receive radiation beams to provide a second two-way radiation beam.

Further, a second transmit radiation beam of the plurality of transmit radiation beams is combined with the second receive radiation beam of the plurality of receive radiation beams to provide a third two-way radiation beam. The second transmit radiation beam of the plurality of transmit radiation beams is combined with a third receive radiation beam of the plurality of receive radiation beams to provide a fourth two-way radiation beam. The second transmit radiation beam of the plurality of transmit radiation beams is combined with a fourth receive radiation beam of the plurality of receive radiation beams to provide a fifth two-way radiation beam.

Yet further, a third transmit radiation beam of the plurality of transmit radiation beams is combined with the fourth receive radiation beam of the plurality of receive radiation beams to provide a sixth two-way radiation beam. The third transmit radiation beam of the plurality of transmit radiation beams is combined with a fifth receive radiation beam of the plurality of receive radiation beams to provide a seventh two-way radiation beam. The third transmit radiation beam of the plurality of transmit radiation beams is combined with a sixth receive radiation beam of the plurality of receive radiation beams to provide an eighth two-way radiation beam.

A fourth transmit radiation beam of the plurality of transmit radiation beams is combined with the sixth receive radiation beam of the plurality of receive radiation beams to provide a ninth two-way radiation beam. Finally, the fourth transmit radiation beam of the plurality of transmit radiation beams is combined with a seventh receive radiation beam of the plurality of receive radiation beams to provide a tenth two-way radiation beam.

In accordance with another aspect of the present invention, predetermined ones of the plurality of transmit beams and predetermined ones of the plurality of receive beams are combined to form seven two-way radiation beams. More particularly, a first transmit radiation beam of the plurality of transmit radiation beams is combined with a first receive radiation beam of the plurality of receive radiation beams to provide a first two-way radiation beam. A second transmit radiation beam of the plurality of transmit radiation beams is combined with the first receive radiation beam of the plurality of receive radiation beams to provide a second two-way radiation beam. The second transmit radiation beam of the plurality of transmit radiation beams is combined with a second receive radiation beam of the plurality of receive radiation beams to provide a third two-way radiation beam.

Further, a third transmit radiation beam of the plurality of transmit radiation beams is combined with the second receive radiation beam of the plurality of receive radiation beams to provide a fourth two-way radiation beam. The third transmit radiation beam of the plurality of transmit radiation beams is combined with a third receive radiation beam of the plurality of receive radiation beams to provide a fifth two-way radiation beam. A fourth transmit radiation beam of the plurality of transmit radiation beams is combined with the third receive radiation beam of the plurality of receive radiation beams to provide a sixth two-way radiation beam. Finally, the fourth transmit radiation beam of the plurality of transmit radiation beams is combined with a fourth receive radiation beam of the plurality of receive radiation beams to provide a seventh two-way radiation beam.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features of this invention, as well as the invention itself, may be more fully understood from the following description of the drawings in which:

FIG. **1** is a top plan view of an asymmetric antenna array in accordance with an embodiment of the present invention;

FIG. **2** is a block diagram of a beam switching system adapted for coupling to the asymmetric antenna array, as shown in FIG. **1**;

FIG. **3** is a block diagram of beam combining system adapted for coupling to the asymmetric antenna array, as shown in FIG. **1**;

FIG. **4** is an illustration of a plurality of beams generated by a Butler Matrix circuit of the beam combining system of FIG. **3**;

FIG. **4**A is an illustration of an overlay of a plurality of receive beams generated by the beam combining system of FIG. **3** and a plurality of transmit beams generated by the beam switching system of FIG. **2**;

FIG. **5** is a graph illustrating radiation patterns associated with the plurality of receive beams generated by the beam combining system of FIG. **3**;

FIG. **6** is a top plan view of an asymmetric antenna array in accordance with another embodiment of the present invention;

FIG. **7** is a block diagram of beam switching system and/or beam combining system adapted for coupling to the asymmetric antenna array, as shown in FIG. **6**;

FIG. **7**A is a block diagram of another embodiment of the beam switching system and/or beam combining system adapted for coupling to the asymmetric antenna array, as shown in FIG. **6**;

FIG. **8** is an illustration of an overlay of a plurality of receive beams and a plurality of transmit beams generated by the beam switching system and/or beam combining system of FIG. **7**;

FIG. **9** is a graph illustrating radiation patterns associated with the plurality of receive beams generated by the beam switching system and/or beam combining system of FIG. **7**;

FIG. **10** is a top plan view of an asymmetric antenna array in accordance with another embodiment of the present invention;

FIG. **11** is a block diagram of beam switching system adapted for coupling to the asymmetric antenna array, as shown in FIG. **10**;

FIG. **12** is a graph illustrating radiation patterns associated with the plurality of receive beams generated by the beam combining system of FIG. **3**, which is adapted for coupling to the asymmetric antenna array, as shown in FIG. **10**;

FIG. **13** is an illustration of an overlay of a plurality of receive beams and a plurality of transmit beams respectively generated by the beam switching system and beam combining system of FIGS. **2** and **3**; and

FIG. **14** is a graph illustrating radiation patterns representing a predetermined combination of the plurality of receive beams and the plurality of transmit beams as provided by the beam combining system of FIG. **3**.

DETAILED DESCRIPTION OF THE INVENTION

Referring to FIG. **1**, set forth is an asymmetric antenna array **10** provided from a substrate **11** having a length L and width W. The asymmetric antenna array **10** includes a first plurality of antenna elements disposed on the substrate **11** to provide a transmit antenna array **12** and a second plurality of antenna elements disposed on the substrate **11** to provide a receive antenna array **14**. In one embodiment, the transmit antenna array **12** includes four rows **16***a*–**16***d* and three columns **18***a*–**18***c* and the receive antenna array **14** includes eight rows **20***a*–**20***h* and six columns **22***a*–**22***f*. Thus, the transmit antenna array **12** includes twelve radiating elements (or more simply "radiators" or "elements"), generally denoted **24**, with four elements in azimuth and three elements in elevation. Additionally, the receive antenna array **14** includes forty-eight radiating elements (or more simply "radiators" or "elements"), generally denoted **26**, with eight elements in azimuth and six elements in elevation.

It should be understood that a number of permutations of arrangements and quantities of radiators **24** can be disposed on the substrate **11** to define the transmit array **12** as long as the quantity of radiators **24** differs from the quantity of radiators **26** disposed on the substrate **11** to define the receive array **14**. Similarly, it should be understood that a number of permutations of arrangements and quantities of radiators **26** can be disposed on the substrate **11** to define the receive array **14** as long as the quantity of radiators **26** differs from the quantity of radiators **24** disposed on the substrate **11** to define the transmit array **12**. As will be described below in conjunction with FIGS. **2**–**5**, the transmit array **12** is coupled to a transmit signal path and the receive array **14** is coupled to a receive signal path.

Referring to FIG. **2**, in the exemplary embodiment, a beam switching system **40** includes a beamformer circuit **41** which in this particular embodiment is shown as a Butler matrix beam forming network **41** having a plurality of antenna element ports **42**a–**42**d generally denoted **42** and a plurality of switch ports **44**a–**44**d. In an embodiment, the antenna element port **42** can be coupled to a transmit antenna array, such as the transmit antenna array **12** of FIG. **1**, which is described in detail below.

The transmission lines **45**a–**45**d respectively couple each of the switch ports **44**a–**44**d of the beamformer circuit **41** to a switched beam combining circuit **46**. Optionally, one, some or all of the transmission lines **45**a–**45**d can include amplitude control elements **43**a–**43**d which may be provided, for example, as an attenuator or as an amplifier. The amplitude control elements **43**a–**43**d may be used for example, to control the signal levels in individual beams emitted from each of the corresponding antenna element ports **42**a–**42**d, as described above. Although not shown in the figures, similar amplitude control elements can also be coupled between the beamformer circuit **41** and some or all of the antenna element ports **42**a–**42**d, which provides additional control to the signal levels in individual beams emitted from each of the antenna element ports **42**a–**42**d.

In the exemplary embodiment, the signal path between beamformer port **44**a and switch port **47**a includes an amplitude control element, as does the signal path between beamformer port **44**d and switch port **47**d. In this arrangement, the signal levels in individual beams emitted from each of the antenna element ports **42**a–**42**d will be substantially equivalent. In other words, the signal levels in individual beams emitted from each of the antenna element ports **42**a–**42**d will include substantially equivalent radiant energy.

The switched beam combining circuit **46** is here provided from a single pole four throw switch **46** having a common port **49** coupled to the output port of the beam switching system **40**. The common port **49** is coupled to a signal generator **50**.

In one embodiment, each of the antenna element ports **42**a–**42**d are coupled to corresponding ones of the four rows **16**a–**16**d of the transmit antenna array **12**, shown in FIG. **1**. It should be understood that the plurality of antenna element ports **42**a–**42**d of the antenna port **42** is scalable. Thus, in the event that an array antenna having more than four rows was used, it would be possible to make appropriate changes to the beamformer circuit to provide the beamformer circuit having an appropriate number of antenna ports **42**.

Referring now to FIG. **3**, a beam combining system **80** includes a beamforming circuit **60** having a plurality of antenna element ports **62**a–**62**h generally denoted **62** and a plurality of switch ports **64**a–**64**h generally denoted **64**. In this exemplary embodiment, the beamforming circuit **60** is shown as a Butler matrix beamforming network. In an embodiment, the antenna element port **62** can be coupled to a receive antenna array, such as the receive antenna arrant **14** of FIG. **1**, which is described in detail below.

The switch ports **64** are coupled through transmission lines **66**a–**66**h to a switched beam combining circuit **70**. As is known, the port phasing for a Butler matrix have 180° phase difference and the curved signal paths **66**a, **66**c, **66**f, **66**h represent 180° differential line lengths required to bring all of the ports in phase with each other. The switched beam combining circuit **70** is here provided from a pair of single pole four throw switches **74**, **75**. Each of the switches **74**, **75** include a common port **71**, **73** coupled to respective output ports **76**, **78** of a power divider circuit **77**. The power divider circuit **77** is provided such that a signal fed to an input port **79** has an equal phase and power level at the output ports **76**, **78**. In this example, the port **79** is coupled to a receiver circuit **82**, via an output port **81**.

In one embodiment, the plurality of antenna element ports **62**a–**62**h are coupled to corresponding ones of the rows **20**a–**20**h of the receive antenna array **14**, shown in FIG. **1**. It should be understood that the plurality of antenna element ports **62**a–**62**h of the antenna port **62** is scalable to accommodate a plurality of different receive antenna arrays (not shown) having a plurality of rows of radiators or elements.

Referring to FIG. **4**, in this particular embodiment, the Butler beamforming circuit **60** (FIG. **3**) forms eight beams **120**a–**120**h. That is, by providing an input signal to one of the plurality of antenna ports **62** of the Butler matrix **60**, which input signal is provided from the receive antenna **26**, the Butler matrix **60** generates a corresponding one of the beams **120**a–**120**h at a corresponding one of the plurality of switch ports **64** thereof. The calculations for determining the beam locations can be found using the equations below:

Wavelength (inches):	$\lambda := \frac{11.81}{24}$
Number of Elements:	$N := 8$
Element Spacing (Azimuth):	$d := .223$
Beam Location (Degrees):	$\text{beamloc}(M) := \text{asin}\left[\frac{\lambda}{N \cdot d} \cdot \left(M - \frac{1}{2}\right)\right] \cdot \frac{180}{\pi}$
Beam Number:	$M := 1 \ldots \frac{N}{2}$

If the array is provided having an array lattice spacing of 0.223" in azimuth, the beam locations shown in FIG. **4** are provided. In one embodiment, the differential line length value, n is selected to be 1/16 λ which corresponds to 0.0127 inch at a frequency of 24 GHz. FIG. **7** also illustrates which beam-ports in FIG. **6** produce which beams.

Referring now to FIG. **4**A, a calculated antenna radiation pattern **122** includes four transmit beams **123**a–**123**d and seven receive beams **124**a–**124**g which can be used in a radar system. The four transmit beams are formed by feeding a transmit signal produced by signal source **50** (FIG. **2**) through the switch **46**. Depending upon the switch path which is selected, a signal is provided to one of the Butler matrix ports **44**a–**44**d (FIG. **2**). The Butler beamforming circuit **40** then forms one of the four transmit antenna beams **123**a–**123**d. That is, by providing an input signal to one of the Butler matrix input ports **44**a–**44**d (FIG. **2**), the transmit antenna **12** (FIG. **1**) produces a corresponding one of the beams **123**a–**123**d.

The seven receive beams **124**a–**124**g are provided by combining predetermined ones of the eight beams **120**a–**120**h (FIG. **4**) formed by the Butler Matrix **60** (FIG. **3**) as discussed above. Adjacent beams (e.g. beams **120**a, **120**b from FIG. **4**) can be combined to produce beam **124**a as illustrated in FIG. **4**A. Since beams out of a Butler Matrix by definition are orthogonal, combining beams in azimuth produces a cos(θ) taper with a peak sidelobe level of 23 dB (with respect to the beam maximum).

The locations of the combined received beams are listed in the Table below.

TABLE

Combined Beam	Beam Location
8,1	0
4,8 & 1,5	+/−16
6,4 & 5,3	+/−34
2,6 & 3,7	+/−57

In elevation, there is also a 25 dB Chebyshev taper and a 15° beam steer.

Referring to FIG. **5**, a two-way radiation pattern having seven antenna beams **130***a*–**130***g* is produced by an array antenna having an array of antenna elements provided as described above in conjunction with FIG. **1** and having the transmit array **12** coupled to a transmit path of the type described above in conjunction with FIG. **2** and having the receive array **14** coupled to a receive path of the type described above in conjunction with FIG. **3**.

Referring to FIG. **6**, set forth is another embodiment of an asymmetric antenna array **210** in accordance with the present invention. The asymmetric antenna array **210** can be disposed on a substrate **211** having a length L and width W. The asymmetric antenna array **210** includes a first plurality of antenna elements disposed on the substrate **211** to provide a transmit antenna array **212** and a second plurality of antenna elements disposed on the substrate **211** to provide a receive antenna array **214**. In one embodiment, the transmit antenna array **212** includes four rows **216***a*–**216***d* and three columns **218***a*–**218***c* and the receive antenna array **214** includes four rows **220***a*–**220***d* and six columns **222***a*–**222***f*. Thus, the transmit antenna array **212** includes twelve radiating elements (or more simply "radiators" or "elements"), generally denoted **224**, with four elements in azimuth and three elements in elevation. Additionally, the receive antenna array **214** includes twenty-four radiating elements (or more simply "radiators" or "elements"), generally denoted **226**, with four elements in azimuth and six elements in elevation.

It should be understood that a number of permutations of arrangements and quantities of radiators **224** can be disposed on the substrate **211** to define the transmit array **212** as long as the quantity of radiators **224** differs from the quantity of radiators **226** disposed on the substrate **211** to define the receive array **214**. Similarly, it should be understood that a number of permutations of arrangements and quantities of radiators **226** can be disposed on the substrate **211** to define the receive array **214** as long as the quantity of radiators **226** differs from the quantity of radiators **224** disposed on the substrate **211** to define the transmit array **212**.

Referring to FIG. **7**, in the exemplary embodiment, a beam switching system **240** includes a beamformer circuit **241**, which in this particular embodiment is shown as a Butler matrix beam forming network **241** having a plurality of antenna element ports **242***a*–**242***d* generally denoted **242** and a plurality of switch ports **244***a*–**244***d*. In one embodiment, the antenna element port **242** can be coupled to a transmit antenna array, such as the transmit antenna array **212** of FIG. **6** (e.g. beam switching system **240** is employed to transmit signals to the transmit antenna array **212**, via the antenna element port **242**), which is described in detail below. In another embodiment, the antenna element port **242** can be coupled to a receive antenna array, such as the receive antenna array **214** of FIG. **6** (e.g. beam switching system **240** is employed to receive signals from the receive antenna array **214**, via the antenna element port **242**), which is also described in detail below.

The transmission lines **245***a*–**245***d* couple each of the switch ports **244***a*–**244***d* to a switched beam combining circuit **246**. Optionally, one, some or all of the transmission lines **245***a*–**245***d* can include an amplitude control element, which is similar to that shown and described above in connection with FIG. **2**. In the exemplary embodiment, the signal path between beamformer port **244***a* and switch port **247***a* includes an amplitude control element as does the signal path between beamformer port **244***d* and switch port **247***d*.

The switched beam combining circuit **246** is here provided from a single pole four throw switch **246** having a common port **249** coupled to the output port of the beam switching system **240**. The common port **249** can be coupled to a signal generator **250** when the beam switching system **240** is employed to transmit a plurality of signal to the transmit antenna **224** (FIG. **6**), via the antenna port **242**. In an embodiment, each of the antenna element ports **242***a*–**242***d* are coupled to corresponding ones of the four rows **216***a*–**216***d* of the transmit antenna array **212**, as shown in FIG. **6**. It should be understood that the plurality of antenna element ports **242***a*–**242***d* of the antenna port **242** is scalable. Thus, in the event that a transmit array antenna **212** having more than four rows was used, it would be possible to make appropriate changes to the beamformer circuit **241** of the beam switching system **240** to provide the beamformer circuit **241** having an appropriate number of antenna ports **242**.

In addition, it should be understood that a beam combining system (not shown) can be similarly constructed and arranged as the beam switching system **240**. Therefore, for illustrative purposes, the beam switching system **240** can be redefined as the beam combining system **240**, where like components are referred to using like reference designations. The beam combing system **240** includes a signal receiver circuit **252** coupled to the common output port **249** of the switch **246**. In an embodiment, each of the antenna element ports **242***a*–**242***d* are coupled to corresponding ones of the four rows **220***a*–**220***d* of the receive antenna array **214**, shown in FIG. **6**. It should be understood that the plurality of antenna element ports **242***a*–**242***d* of the antenna port **242** is scalable. Thus, in the event that a receive array antenna **214** having more than four rows was used, it would be possible to make appropriate changes to the beamformer circuit **241** of the beam combining circuit **240** to provide the beamformer circuit **241** having an appropriate number of antenna ports **242**.

Referring to FIG. **7**A, shown is another exemplary embodiment of a beam switching system and/or beam combining system **240'**, which is similarly constructed and arranged as the beam switching system and/or beam combining system **240**, as shown and described above with respect to FIG. **7**, where like components are referred to using like reference designations. In FIG. **7**A, the beam switching system and/or beam combining system **240'** further includes a number of phase shifters **243***a*, **243***b*, **243***c* and **243***d*, which are coupled between each of the respective antenna element ports **242***a*, **242***b*, **242***c* and **242***d* and the beamformer circuit **241**.

During transmission of signals from the signal generator **250** through the beam switching system and/or beam combining system **240'** to the transmit antenna array **212** (FIG. **6**), via the antenna element ports **242***a*, **242***b*, **242***c* and **242***d*, each of the corresponding phase shifters **243***a*, **243***b*, **243***c* and **243***d* introduce a predetermined phase shift to the transmitted signal, which introduces a corresponding phase shift or "squint" to the antenna beam signal emitted from the transmit antenna array **212**. In one embodiment, the phase shifters **243***a*, **243***b*, **243***c* and **243***d* can be constructed and arranged to introduce a phase shift or squint to the antenna beam emitted from the transmit antenna array **212** of approximately one-half a beam width in a first predetermined direction (e.g. to the left).

Similarly, when the antenna receives a signal (e.g. receive antenna array **214** on FIG. **6** receives a signal), the signal is fed to ports **242***a*–**242***d* and subsequently propagates through phase shifters **243***a*, **243***b*, **243***c* and **243***d*. The phase shifters **243***a*–**243***d* introduce a predetermined phase shift to the received signal, which introduces a corresponding shift or squint to the positions of the receive antenna beams produced by the receive antenna array. In one embodiment, the phase shifters **243***a*, **243***b*, **243***c* and **243***d* can be constructed and arranged to introduce a shift or squint to the antenna beam signal received from the receive antenna array **214** of approximately one-half a beam width in a second predetermined direction (e.g. to the right).

Referring to FIG. **8**, shown is an overlay **322** (illustration does not depict actual beam shapes and locations) and combination of transmit beams **323***a*–**323***d* and receive beams **324***a*–**324***d*, which operate to form the seven two-way beams **325***a*–**325***g*, as described herein. In the exemplary embodiment, the transmit beams **323***a*–**323***d* and receive beams **324***a*–**324***d* are squinted or phase-shifted approximately one-half a beam width in opposite direction with respect to each other. Furthermore, adjacent transmit beams **323***a*–**323***d* and receive beams **324***a*–**324***d* can be combined to form the seven two-way beams **325***a*–**325***g*.

In an embodiment, the transmit beam **323***a* can be combined with receive beam **324***a* to form two-way beam **325***a*. Further, the transmit beam **323***b* can be combined with receive beam **324***a* to form two-way beam **325***b*. The transmit beam **323***b* can be combined with receive beam **324***b* to form two-way beam **325***c*. The transmit beam **323***c* can be combined with receive beam **324***b* to form two-way beam **325***d*. The transmit beam **323***c* can be combined with receive beam **324***c* to form two-way beam **325***e*. The transmit beam **323***d* can be combined with receive beam **324***c* to form two-way beam **325***f*. Finally, the transmit beam **323***d* can be combined with receive beam **324***d* to form two-way beam **325***g*.

Referring to FIG. **9**, a two-way radiation pattern having seven antenna beams **330***a*–**330***g* is produced by an array antenna having an array of antenna elements provided as described above in conjunction with FIG. **6** and having the transmit antenna array **212** and the receive antenna array **214** coupled to a transmit and/or receive path of the type described above in conjunction with FIG. **7**. FIG. **9** shows a typical two-way antenna radiation pattern **330** corresponding to the seven two-way beams **325***a*–**325***g*, as shown in FIG. **8**. The number of beams and beam coverage are substantially the same as that shown and described above with respect to FIG. **5**. The side-lobe levels associated with each of the seven two-way beams **330***a*–**330***g* are approximately below the 40 dB level. Further, it should be recognized that any loss in transmit gain or receive sensitivity is relatively insignificant and does not necessitate amplification using additional amplifiers. In addition, it should also be recognized that even though the seven two-way beams **330***a*–**330***g* include slightly broader beamwidths than the seven two-way beams **130***a*–**130***g* of FIG. **5**, which affects the degree to which the detection coverage zone can be shaped, the seven two-way beams **330***a*–**330***g* remain particularly useful in radar system applications.

Referring to FIG. **10**, set forth is another embodiment of an asymmetric antenna array **410** in accordance with the present invention. The asymmetric antenna array **410** can be disposed on a substrate **411** having a length L and width W. The asymmetric antenna array **410** includes a first plurality of antenna elements disposed on the substrate **411** to provide a transmit antenna array **412** and a second plurality of antenna elements disposed on the substrate **411** to provide a receive antenna array **414**. In one embodiment, the transmit antenna array **412** includes one row **416** and three columns **418***a*–**418***c* and the receive antenna array **414** includes eight rows **420***a*–**420***h* and six columns **422***a*–**422***f*. Although the respective row(s) and columns of the transmit antenna array **412** and the receive antenna array **414** have been respectively disclosed as being vertically oriented and horizontally oriented, it should be understood that these definitions can be modified to re-define the vertically oriented radiators as columns and the horizontally oriented radiators as rows.

In an embodiment, the transmit antenna array **412** includes three radiating elements (or more simply "radiators" or "elements"), generally denoted **424**, with one element in azimuth and three elements in elevation. Additionally, the receive antenna array **414** includes forty-eight radiating elements, generally denoted **426**, with eight elements in azimuth and six elements in elevation.

Although not specifically shown, it should be understood that the transmit antenna array **412** can include one row **416** and one column, such as column **418***a*. Thus, the transmit antenna array **412** can include a single radiating element (or more simply "radiator" or "element"), generally denoted **424**, with one element in azimuth and one elements in elevation.

It should also be understood that a number of permutations of arrangements and quantities of radiators **424** can be disposed on the substrate **411** to define the transmit array **412** as long as the quantity of radiators **424** which define the transmit array differs from the quantity of radiators **426** which define the receive antenna array **414**. Similarly, it should be understood that a number of permutations of arrangements and quantities of radiators **426** which define the receive array **414** as long as the quantity of radiators **426** differs from the quantity of radiators **424** which define the transmit array **412**.

Referring to FIG. **1**, in the exemplary embodiment, a beam switching system **440** includes a beamformer circuit **441**, which in this particular embodiment is shown as a Butler matrix beam forming network **441** having at least one antenna element port **442***a* and at least one switch port **444**. In the exemplary embodiment, the antenna port **442** is coupled to the row **416** of the transmit antenna array **412**, as shown in FIG. **10**. Further, the switch port **444** is coupled to an output **450***a* of a signal generator **450**. It should be understood that the at least one antenna element **442***a* of the antenna port **442** is scalable. Thus, in the event that a transmit antenna array **412** having more than one row was used, it would be possible to make appropriate changes to the beamformer circuit **441** of the beam switching system **440** to provide the beamformer circuit **441** having an appropriate number of antenna ports **442**.

Referring again to FIG. **3**, the beam combining system **80** can be similarly coupled to the receive antenna array **414** of FIG. **10** as that previously shown and described above for coupling the beam combining system **80** to the receive antenna **26** of FIG. **3**. Thus, a plurality of signals received by the receive antenna array **414** of FIG. **10** can be realized at the receiver circuit **82**, via the output **81**, as shown in FIG. **3**.

Referring to FIG. **12**, a two-way radiation pattern having seven antenna beams **460***a*–**460***g* is produced by an array antenna having an array of antenna elements as described above in conjunction with FIG. **10**. The side-lobe levels associated with each of the seven two-way beams **460***a*–**460***g* are approximately below the 20 dB level. In the exemplary embodiment, it should be understood that an increase in the transmit energy or power provided to the transmit antenna can increase the system performance. Thus, transmit energy or power provided to the transmit antenna can be controlled to accommodate a particular application for the asymmetric antenna array, while at the same time providing a cost efficient asymmetric antenna array.

Although not specifically shown, it should be understood that the asymmetric antenna arrays **10**, **210** and **410** respectively shown in FIGS. **1**, **6** and **10**, can each be substituted with a plurality of other types of antenna arrays having a plurality of other types of radiators arranged in a plurality of configurations without departing from the spirit and scope of the present invention.

In another embodiment of the present invention, the asymmetric antenna array **10**, the beam switching system **40** and the beam combining system **80**, as respectively shown and described above in detail with respect to FIGS. **1**–**3**, can be controlled to provide ten two-way beams **515***a*–**515***j*, which will be described below in connection with FIGS. **13** and **14**.

Referring now to FIG. **13**, shown is an overlay **500** (illustration does not depict actual beam shapes and locations) and combination of transmit beams **505***a*–**505***d* and receive beams **510***a*–**510***g*, which operate to form the ten two-way beams **515***a*–**515***j*, as described herein. In the exemplary embodiment, adjacent transmit beams **505***a*–**505***d* and receive beams **510***a*–**510***d* can be combined to form the ten two-way beams **515***a*–**515***g*.

In an embodiment, the transmit beam **505***a* can be combined with receive beam **510***a* to form a first two-way beam **515***a*. Further, the transmit beam **505***a* can be combined with receive beam **510***b* to form a second two-way beam **515***b*. The transmit beam **505***b* can be combined with receive beam **510***b* to form a third two-way beam **515***c*. The transmit beam **505***b* can be combined with receive beam **510***c* to form a fourth two-way beam **515***d*. The transmit beam **505***b* can be combined with receive beam **510***d* to form a fifth two-way beam **515***e*. The transmit beam **505***c* can be combined with the receive beam **510***d* to form a sixth two-way beam **515***f*. The transmit beam **505***c* can be combined with receive beam **510***e* to form a seventh two-way beam **515***g*. The transmit beam **505***c* can be combined with receive beam **510***f* to form an eighth two-way beam **515***h*. The transmit beam **505***d* can be combined with receive beam **510***f* to form a ninth two-way beam **515***i*. The transmit beam **505***d* can be combined with receive beam **510***g* to form a tenth two-way beam **515***j*.

Although not specifically described herein, it should be understood that in accordance with various embodiments of the present invention, there exists a plurality of permutations of combinations of transmit and receive beams that can be formed to provide a number of two-way beams having various attributes. For example, greater than ten two-way beams can be formed by combining the transmit and receive beams in other manners than specifically provided herein. Furthermore, fewer than ten two-way beams can be formed, such as seven two-way beams as described above in detail with respect to FIG. **8**.

Referring to FIG. **14**, a two-way radiation pattern **600** having ten antenna beams **600***a*–**600***j* is produced by the asymmetric antenna array **10** of FIG. **1**, which includes the transmit antenna array **12** coupled to the beam switching system **40** of FIG. **2** and the receive antenna array **14** coupled to the beam combining system **80** of FIG. **3**. In FIG. **14**, the ten antenna beams **600***a*–**600***j* of the two-way antenna radiation pattern **600** correspond to the ten two-way beams **515***a*–**515***j*, as shown in FIG. **13**. The side-lobe levels associated with each of the ten antenna beams **600***a*–**600***j* of the two-way antenna radiation pattern **600** are approximately below the 27 dB level. Furthermore, the ten antenna beams **600***a*–**600***j* of the two-way antenna radiation pattern **600** provides many appreciable advantages, such providing a detection zone having a relatively higher beam resolution, which is more conducive to shaping.

Having described the preferred embodiments of the invention, it will now become apparent to one of ordinary skill in the art that other embodiments incorporating their concepts may be used. It is felt therefore that these embodiments should not be limited to disclosed embodiments but rather should be limited only by the spirit and scope of the appended claims.

What is claimed is:

1. A method of forming a plurality of two-way beams using a transmit and receive system, the method comprising:
- controlling a transmit antenna array of the transmit and receive system to provide a plurality of transmit beams;
- simultaneously forming a first plurality of receive beams via a beamformer network;
- controlling a switched beam combining circuit of a receive antenna array of the transmit and receive system to form a second plurality of receive beams wherein the controlling comprises combining selected ones of the formed beams via a switch network; and
- combining predetermined ones of the plurality of transmit beams and predetermined ones of the second plurality of receive beams to form the plurality of two-way beams.

2. The method of claim **1**, wherein controlling the transmit antenna array includes controlling a beam switching system coupled to the transmit antenna array to provide the plurality of transmit beams.

3. The method of claim **1**, wherein controlling the switched beam combining circuit of the receive antenna array includes controlling a plurality of single-pole, multi-throw switches to provide the second plurality of receive beams.

4. The method of claim **1**, wherein combining includes combining a first transmit beam of the plurality of transmit beams with at least one of the second plurality of receive beams to provide a first one of the plurality of two-way beams.

5. The method of claim **4**, wherein combining further includes combining the first transmit beam of the plurality of transmit beams with a second receive beam of the plurality of receive beams to provide a second one of the plurality of two-way beams.

6. The method of claim **5**, wherein combining further includes combining a second transmit beam of the plurality of transmit beams with the second receive beam of the plurality of receive beams to provide a third two-way beam of the plurality of two-way beams.

7. The method of claim **6**, wherein combining further includes combining the second transmit beam of the plurality of transmit beams with a third receive beam of the plurality of receive beams to provide a fourth two-way beam of the plurality of two-way beams.

8. The method of claim **7**, wherein combining further includes combining the second transmit beam of the plurality of transmit beams with a fourth receive beam of the plurality of receive beams to provide a fifth two-way beam of the plurality of two-way beams.

9. The method of claim **8**, wherein combining further includes combining a third transmit beam of the plurality of transmit beams with the fourth receive beam of the plurality of receive beams to provide a sixth two-way beam of the plurality of two-way beams.

10. The method of claim **9**, wherein combining further includes combining the third transmit beam of the plurality of transmit beams with a fifth receive beam of the plurality of receive beams to provide a seventh two-way beam of the plurality of two-way beams.

11. The method of claim **10**, wherein combining further includes combining the third transmit beam of the plurality of transmit beams with a sixth receive beam of the plurality of receive beams to provide an eighth two-way beam of the plurality of two-way beams.

12. The method of claim **11**, wherein combining further includes combining a fourth transmit beam of the plurality of transmit beams with the sixth receive beam of the plurality of receive beams to provide a ninth two-way beam of the plurality of two-way beams.

13. The method of claim **12**, wherein combining further includes combining the fourth transmit beam of the plurality of transmit beams with a seventh receive beam of the plurality of receive beams to provide a tenth two-way beam of the plurality of two-way beams.

14. The method of claim **4**, wherein combining further includes combining a second transmit beam of the plurality of transmit beams with the first receive beam of the plurality of receive beams to provide a second two-way beam of the plurality of two-way beams.

15. The method of claim **14**, wherein combining further includes combining the second transmit beam of the plurality of transmit beams with a second receive beam of the plurality of receive beams to provide a third two-way beam of the plurality of two-way beams.

16. The method of claim **15**, wherein combining further includes combining a third transmit beam of the plurality of transmit beams with the second receive beam of the plurality of receive beams to provide a fourth two-way beam of the plurality of two-way beams.

17. The method of claim **16**, wherein combining further includes combining the third transmit beam of the plurality of transmit beams with a third receive beam of the plurality of receive beams to provide a fifth two-way beam of the plurality of two-way beams.

18. The method of claim **17**, wherein combining further includes combining a fourth transmit beam of the plurality of transmit beams with the third receive beam of the plurality of receive beams to provide a sixth two-way beam of the plurality of two-way beams.

19. The method of claim **18**, wherein combining further includes combining the fourth transmit beam of the plurality of transmit beams with a fourth receive beam of the plurality of receive beams to provide a seventh two-way beam of the plurality of two-way beams.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,183,995 B2
APPLICATION NO. : 10/619020
DATED : February 27, 2007
INVENTOR(S) : Pleva et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1, line 34 delete “trucks boats, airplanes and other vehicle.” and replace with --trucks, boats, airplanes and other vehicles.--.

Column 1, line 64 delete “element” and replace with --elements--.

Column 3, line 48 delete “of beam” and replace with --of a beam--.

Column 3, line 65 delete “of beam” and replace with --of a beam--.

Column 4, line 15 delete “of beam” and replace with --of a beam--.

Column 5, line 2 delete “beam forming” and replace with --beamforming--.

Column 7, line 54 delete “beam forming” and replace with --beamforming--.

Column 8, line 16 delete “signal” and replace with --signals--.

Column 8, line 35 delete “combing” and replace with --combining--.

Column 10, line 31 delete “one elements” and replace with --one element--.

Column 10, line 44 delete “FIG. 1,” and replace with --FIG. 11,--.

Column 12, line 12, delete “such providing” and replace with --such as providing--.

Signed and Sealed this

Eighth Day of April, 2008

Jon W. Dudas

JON W. DUDAS
Director of the United States Patent and Trademark Office